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# FROM RAW IRON TO SEMI-PRODUCT: QUALITY AND CIRCULATION OF MATERIALS DURING THE IRON AGE IN FRANCE*

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*Iron raw materials provide a privileged source of information for the reconstruction of metallurgical techniques and the circulation of iron products. An interdisciplinary approach, combining archaeological and archaeometrical studies of the exemplars known from the French Iron Age, has been undertaken. This enables a new typological classification to be produced that demonstrates a correlation between morphological and structural properties. Through comparison with chronological data, it is possible to propose a reconstruction of the organization of production according to three main periods, which are characterized by the circulation of different qualities of iron and by diverse levels of artisanal specialization.*

*KEYWORDS:* IRON AGE, SEMI-PRODUCTS, BLOOM, TYPOLOGY, TRADE, POST-SMELTING, FORGE, *CHAÎNE OPÉRATOIRE*, WORKSHOP, SPECIALIZATION

## INTRODUCTION

The study of iron metallurgy for the proto-historical period allows us to understand the evolution of technical mastery and the organization of production of a craft that has experienced a high level of quantitative and qualitative development. For this period, numerous iron raw materials are identified (nearly 7000 products are known from the European Iron Age: Berranger 2009a) and they constitute a precious source of documentation. The term 'iron raw product' is used here to designate both blooms and semi-products,[1] as a reserve of metals at different stages of transformation. It does not include finished objects, even if they can be recycled, as they correspond to other trade processes.

Sometimes considered as pre-monetary items, these objects have been subjected to attention since the beginning of the 20th century (Smith 1905). In the majority of cases their discovery context is poorly established, as they have been integrated in deposits. This has often led to their exclusion from the study of the organization of production, but they have nevertheless often been submitted to archaeometrical investigation. They have chiefly been studied for typological classification, these studies being regularly modified to take new discoveries into account (Allen 1967; Kleeman 1981). Nevertheless, most of this research is old and predates the last 15 years (Crew 1994; Doswald 1994).

It is only very recently that iron raw materials have become the focus of a renewed interest from the scientific community. As intermediate products situated between the smelting and forging stages, they function as privileged documents for the characterization of the techniques practised, and can also provide information about circulation networks. A research programme based on them

[1]These objects are called 'semi-products' rather than 'ingots', because—for the direct process—the iron is not derived from the liquid state, but from the solid state.

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has been developed in the laboratory 'Metallurgy and Culture' (IRAMAT–CNRS–UMR 5060) and has resulted in several Ph.D. theses (Bauvais 2007; Pagès 2008; Leroy 2010). One of these theses concerns, more specifically, the Iron Age (Berranger 2009a).

Iron raw materials can present significant morphological and structural variability, depending on the nature of the metal obtained during the smelting process and the result of the treatments used during the bloomsmithing process. The first objective of this work is to characterize their forms and properties at the external (morphology, metrology, aspect of surface) and internal (nature and proportion of impurities, chemical composition) scale, and to compare their characteristics according to their chronological and spatial position. The aim is also to approach the question of their standardization and the spread of metallurgical techniques, as the typology of semi-products is not only correlated with the thermodynamic conditions of formation (in the smelting and refining processes), but also with matters of craftsmanship and workshop traditions.

## METHODOLOGY

The zone of this study encompasses the current territory of France (Fig. 1), in the hope of producing evidence for possible regional specificities or, on the contrary, a wide homogeneity, which could not be seen as being random at this scale. The survey includes artisanal and non-artisanal contexts. Outside artisanal contexts, the objects are complete and yield information

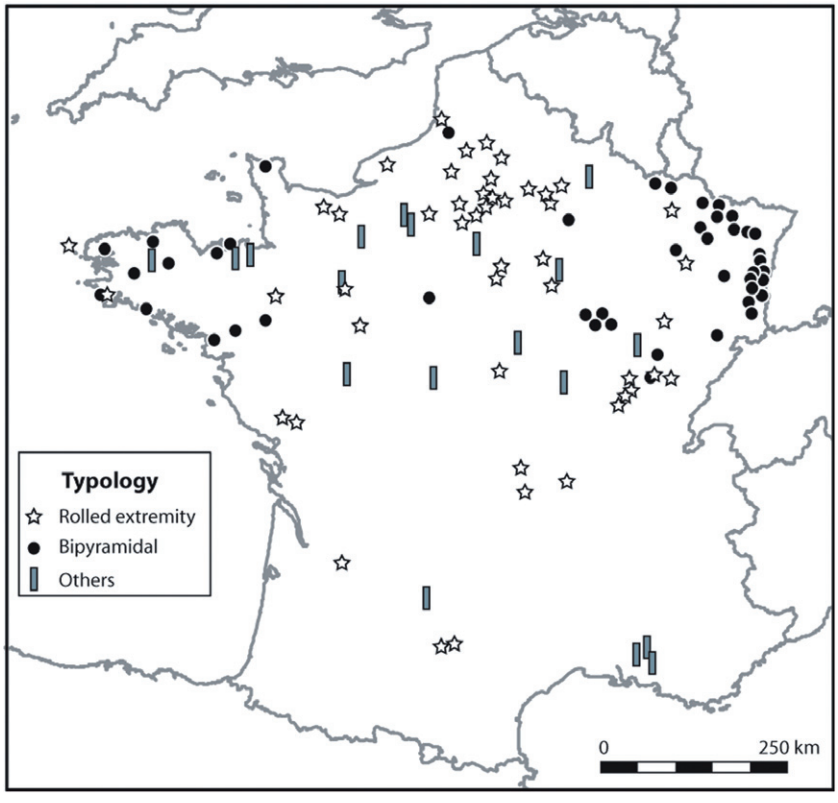


Figure 1 *The distribution of the studied sites, by category of raw iron material.*

on their zone of consumption. It is in artisanal workshops that they deliver the most information on their condition of production and use. The corpus included 128 sites, 77 of which have been studied through bibliographical documentation, while the objects from 51 sites have been submitted to macroscopic investigation. The total number of products surveyed is 1042, more than half of which (564) have been studied at the macroscopic scale. This corpus has been treated using an interdisciplinary approach, according to a protocol that has been validated several times (Mangin 2004; Dillmann and L'Héritier 2007) and that combines archaeological and archaeometrical approaches, from microscopic to chemical analysis of inclusions (174 exemplars have been studied microscopically).

## TERMINOLOGY AND TYPOLOGICAL CLASSIFICATION OF IRON RAW MATERIALS

### *The terminology and principles of the classification*

As iron raw materials are objects intended to be transformed for artisanal purposes, their classification needs to be based upon technical, rather than just morphological, criteria. First, in terms of the technical criteria, the first level of characterization takes into account how advanced the bloomsmithing process is (Fig. 2). Two classes of objects are commonly found. The first class includes those that are, for the most part, not hammered, and often have jagged surfaces. These objects are termed raw products or crude masses of metal (blooms). The second class includes objects whose surfaces are deformed: they are called semi-products. Morphology is the second criterion of classification: five categories have been identified, taking into account the way in which the extremities have been shaped.

The study of the mass of complete bars allows the identification of a threshold that enables the individualization of two types (Fig. 3). The first type includes objects weighing more than 296 g, which are called 'bars' ('quadrangular bar' etc.). The second type gathers together those weighing less than 160 g and the objects are designated as 'draft bars' ('quadrangular draft bar' etc.).[2] If most of the iron objects in circulation during the Iron Age were made from draft bars, the bars would have allowed the fabrication of objects produced in series and some more exceptional pieces, such as weapons, tools, vessels and so on. The variation seen in the detail of the morphology distinguishes the variants (Figs 4 and 5). It could also reflect the habits of individual artisans, workshop traditions or the quality of the iron raw materials.

The macroscopic study was followed by an internal characterization, taking three main domains into account:

(1) The nature and proportion of impurities (slag inclusion and porosities) and their rate of flattening.
(2) The chemical composition (iron/steel etc.), and their proportion and distribution.
(3) The techniques practised, especially thermo-chemical transformations intended to modify the carbon content (cementation/decarburizing). The welding zones in particular have been studied in order to determine the refining processes used.

### *Typology of iron raw materials*

*The raw iron product* Iron can circulate in its raw form, directly after its extraction from the smelting furnace, in the form of an irregular shaped product with a metallic excrescence and

[2]Two exceptions must be pointed out: the bars with a rolled extremity are called 'currency bars' and draft bars with a rolled extremity are called 'socket bars'—even if these terms are inappropriate, because this is their usual denomination in previous studies.

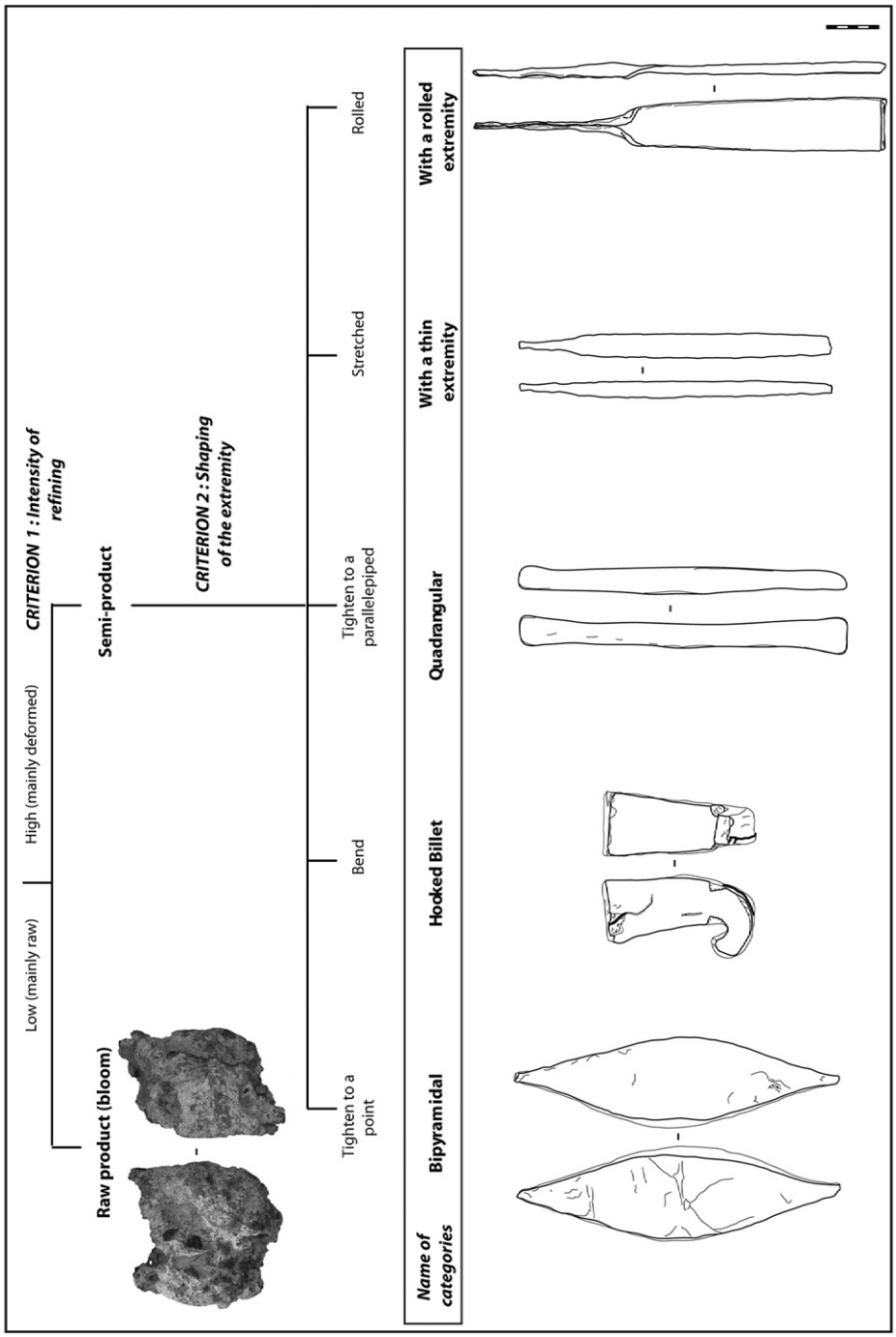


Figure 2 *A typology of the raw iron material.*

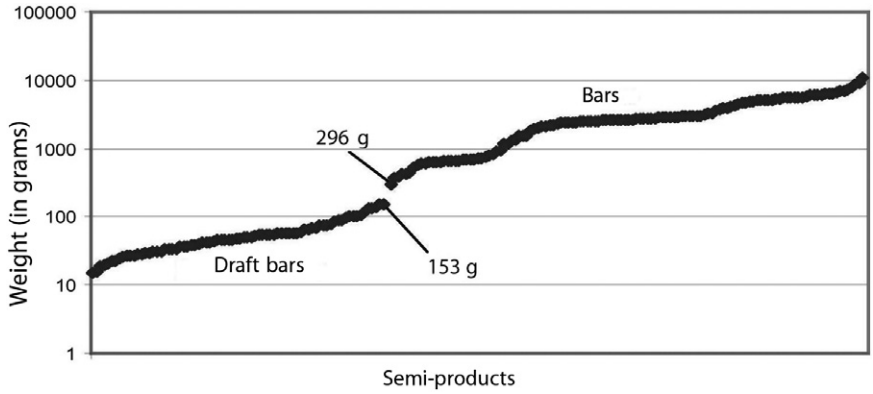


Figure 3 *The mass of the semi-products studied (complete pieces): logarithmic scale.*

holes. It is also possible that the iron circulates as fragments of crude masses of metal (this kind of exchange is also known from ethno-archaeology: Fluzin 2002). In France, six complete pieces and seven fragments have been studied microscopically. They are generally heterogeneous and they contain a lot of impurities: slag, charcoal and porosities. They usually weigh between 2 and 8 kg, with one exemplar having been found that weighs 12.7 kg. It is possible to deduce that they result from a good mastery of the reduction processes, which permitted the production of dense blocks of metal with variable compositions.

*Semi-products* Iron can also circulate in the form of semi-prepared products. Five types are distinguished: the bipyramidal, the hooked-billet, the quadrangular, those with a thin extremity and those with a rolled extremity. In the Iron Age, 99% of the exemplars known are bipyramidal or with a rolled extremity (in Europe, more than 6800 semi-products take these forms out of 6900 known—in France, they represent 996 objects out of 1042 recorded: Berranger 2009a).

The bipyramidals (Fig. 4) In France, this category of semi-products is one of the most represented, with 456 objects coming from 57 sites. These objects have two extremities hammered to a point from a thick section. It is possible to distinguish objects with short extremities (BCS) from others with long and thin extremities (BLD).

Their weight is important: these exemplars weigh between 1 and 8 kg, depending on the variants (one weighting up to 10.6 kg has been recorded). Most of the analytical data come from old analyses (for the French exemplars: France-Lanord 1963; Delamare *et al*. 1982). Three more bars have been studied in the present study and a specific analytical programme concerning these objects is currently being developed at the LMC. At a macroscopic scale, they show deep cracks, and the internal characterization of 11 exemplars reveals a lot of impurities (holes, slag, charcoal), which demonstrates a rapid refining process. They are mainly ferritic or with a low carbon content (less than 0.5% C).

The semi-products with a rolled extremity (Fig. 5) This is the other category that is represented by a large proportion of exemplars, with 540 objects coming from 48 sites. They have a rolled extremity at the end of a flat bar. The heavy bars (CB—'currency bars', weighing from 363 to 2145 g) are distinguished from the light draft bars (BAD—'socket bars', weighing from 15 to

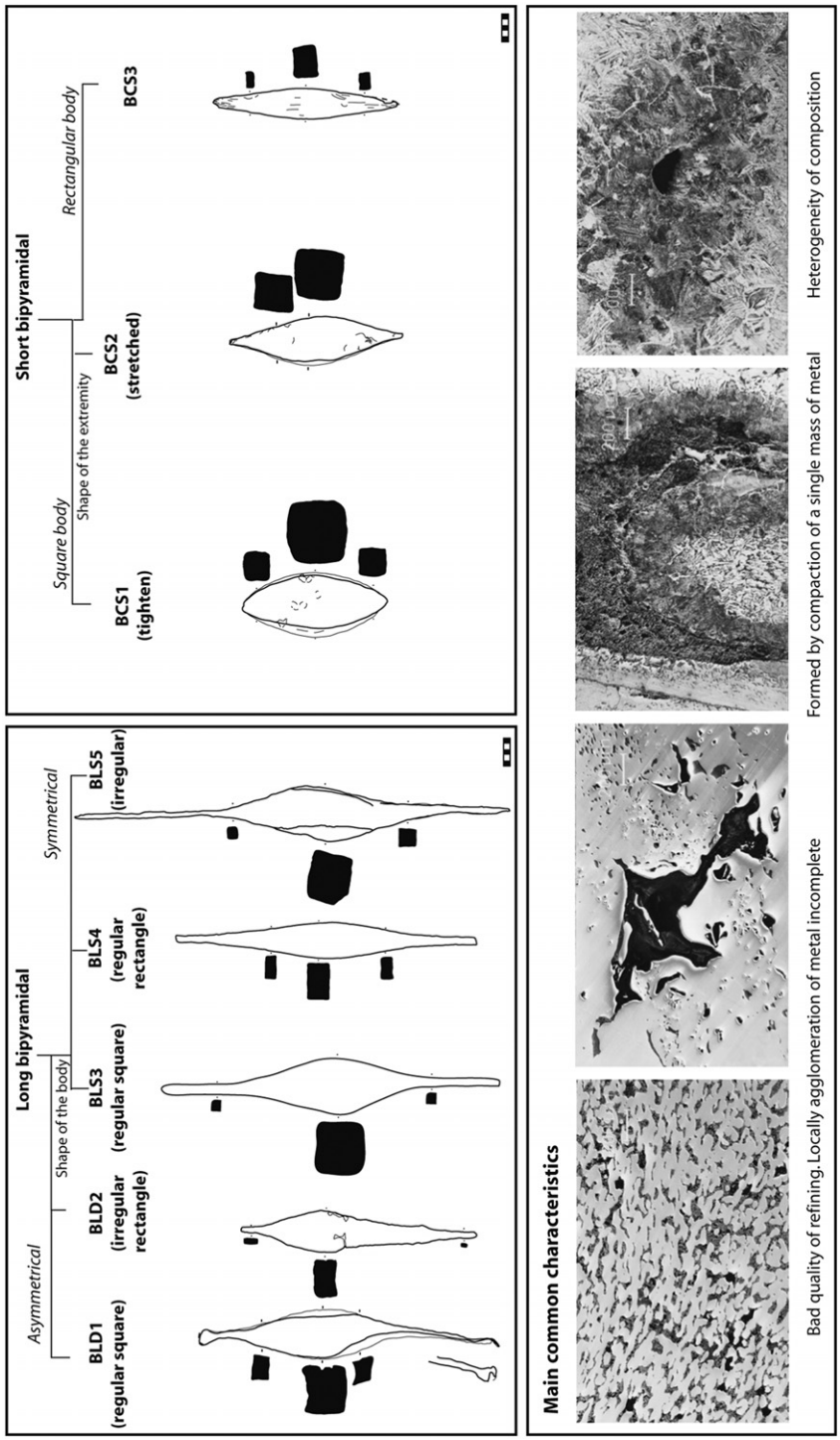


Figure 4 *A typology of the bipyramidal semi-products (variants): morphological and structural characteristics.*

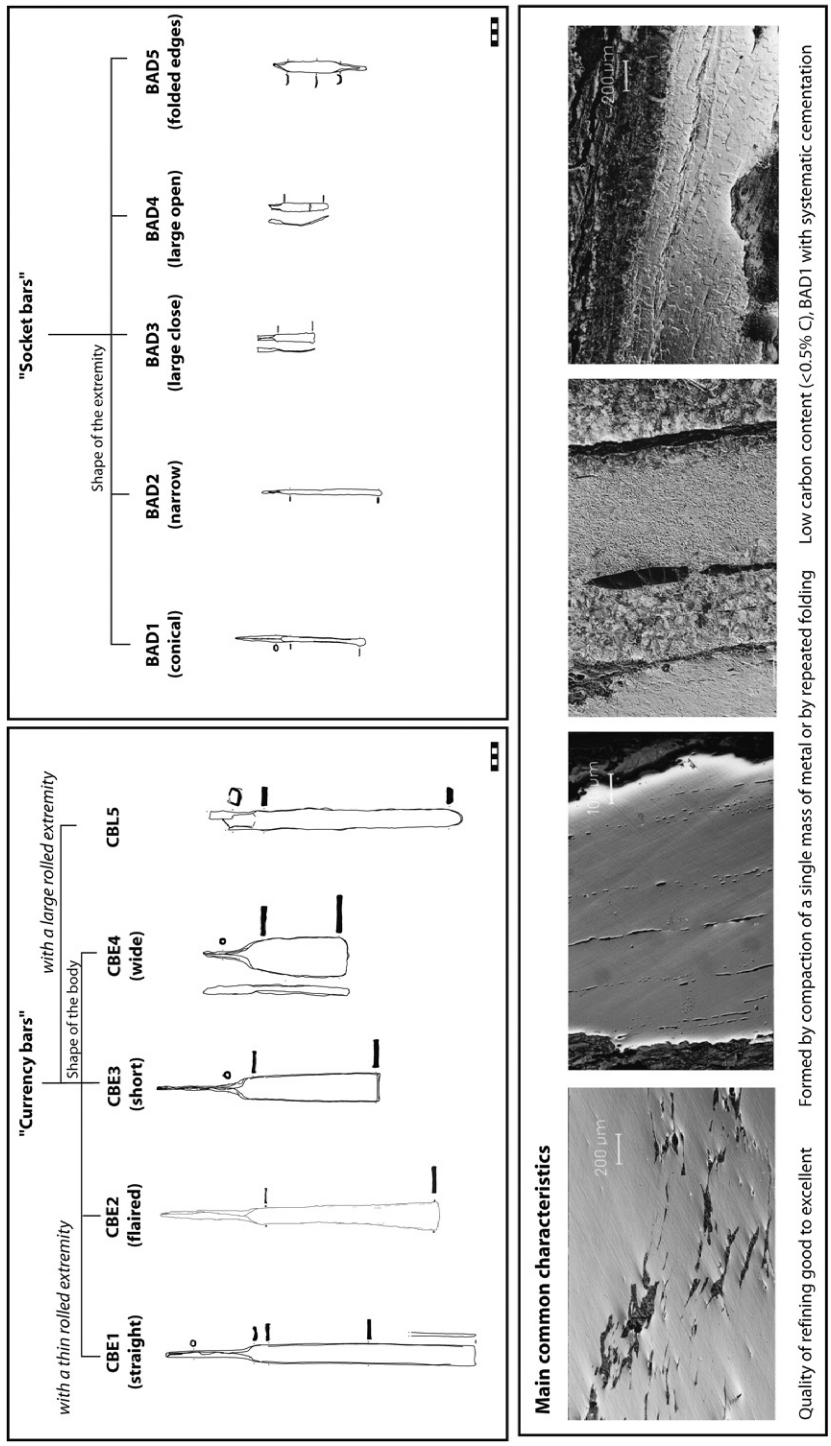


Figure 5 *A typology of the semi-products with a rolled extremity (variants): morphological and structural characteristics.*

200 g). Their external aspect is always good, with no cracks or porosities, and no welding traces are macroscopically visible. In this study, 39 exemplars have been analysed; 13 more have been previously analysed (Dieudonné-Glad *et al*. 2001; Orengo 2003; Bauvais 2007). For several variants, the analysis revealed a careful shaping, resulting from a long and complex refining by repeated folding. They are mainly ferritic or with a low carbon content (less than 0.5% C). One of the variants of the 'socket bars' had been subjected to a cementation process (BAD1: Bauvais 2007; Berranger *et al*. 2007; Berranger 2009a).

The individualization of the other semi-products rests on smaller quantities of exemplars that only allow preliminary observations, which it is necessary to confirm.

The hooked-billet form These exemplars are mainly found in the British Isles, where less than 15 pieces are known (Fell 2003). They are formed by a large body, with a quadrangular base that gets narrower at the other extremity. This last extremity is bent. These heavy products (weighing from 1 to 3 kg) are characterized by a rough surface state: very long and deep cracks and porosities are visible. This reveals an incomplete refining process, which is confirmed by the internal analysis of two exemplars (Fell 2003). These objects seem, on the basis of these analyses, to be mainly ferritic.

Quadrangular semi-products Quadrangular semi-products represent a small proportion of the exemplars in France, with only 20 having been recorded. Their extremities are worked to a parallelepiped form, and can be narrow (BQE) or wide (BQL). Their surfaces are regular and their extremities are small or not transformed. They are light objects (usually weighing between 200 g and 1.3 kg—with one weighing 7 kg). Analyses of the seven exemplars at the LMC reveal that they have been formed by simple deformation. The quality of their refining process is variable, but is usually poor to average. Their composition is mainly ferritic.

The semi-products with a thin extremity These exemplars are the least well known, with less than 15 exemplars having been recorded. They vary greatly in weight, from 680 g for the bars to 15 g for the draft bars. They are constituted by a flat bar and one thin extremity. Their quality of forming and finishing is good. One exemplar has been analysed in the present study, and it reveals an excellent refining quality, and shaping by the deformation of a single mass of metal, at 0.7–0.8% C.

## THE CONDITION OF PRODUCTION OF IRON RAW MATERIALS

### *The* chaîne opératoire *of fabrication*

The raw products (blooms) are those with the shortest *chaîne opératoire* of fabrication: the studied pieces are untransformed or they have only been quickly flattened. The process used to form the bipyramidal semi-products with a short extremity (BC) is very similar. They are, in the majority of cases, obtained from a single mass of metal that has been quickly refined. This results in a compact object, with a very simple shape. For the long bipyramidal (BL) and the hooked-billet forms, the process is continued until an advanced stage, and after a supplementary step of shaping the extremities. The quadrangular semi-products are produced by the deformation of a single mass of metal until a satisfactory level of refinement has been reached that does not exceed a final stage of compaction. They are produced using simple techniques, which require the least investment of time of all the techniques studied here. As only one product with a thin extremity has been studied, it is

not really possible to define their fabrication techniques. The products with a rolled extremity can be fully located in the pre-forming stage and require a lot of time to manufacture, owing to the relative complexity of the techniques used in their production. The compaction is continued until refinement is nearly complete, and some variants are subjected to a supplementary stage of homogenization by repeated folding. The BAD1'socket bars' are also cemented.

Even if it is not possible to link a compaction rate with the quality of the metal, due to the fact that some objects do not need an excellent refining quality to be appropriate to their function (e.g., hardware, anvils), it should be noted that a good refining quality always reveals a high investment in time and a quality of material that is theoretically adapted to the fabrication of a large range of objects. It is probable that these differences of investment in technique and time between categories of semi-products reflect distinct modes of use that will be determined in later sections of this paper.

### *Morphology as an indicator of the internal properties of the metal*

*Texture and quality of refining* The categories, and consequently the morphology, can be correlated with different qualities of refining (Table 1 and Fig. 6). Four groups can be identified when taking into account the quality of refining, the morphology and the mass. It is observed that the objects belonging to the same variant have very close metrological characteristics; in particular, concerning their length and their mass. Some fluctuations can be observed, but these objects were intended to be transformed; therefore, examination of very close similarities could not be justified.

The 'currency bars' are the group of semi-products with the least variability. Their maximal weight range is from 363 g to 2145 g, but the great majority weigh between 500 and 700 g. It is possible that this result is intentional, with the objective of producing specific objects. It is also an indication of the application of identical fabrication techniques for the semi-products of the same variant. Experiments (Crew 1991) have shown that the use of similar bloomsmithing techniques, or blooms of the same mass, results in the production of objects with similar metrological characteristics.

The existence of morphological peculiarities, which can only be interpreted by practical logic, testifies to a will to demonstrate the quality of the metal. It is exemplified by the extremities that are rolled (see also Crew 1991, 1994) or by the extremities of the bipyramidals, which are strongly elongated or flattened in a spatula form. The bipyramidal, quadrangular and hooked-billet exemplars are the rawest and heaviest products. The bars with a rolled or a thin extremity are the lightest and best-refined products (Table 1). In forged products, a certain correlation can be noted: the flatter the product, the better is the quality of refining. However, it is not possible to extrapolate the quality of refining from the metrological characteristics. Here, the correlation that exists between the morphological characteristics (typology) and the quality of refining indicates a probable intention to transmit qualitative information, from the morphology of the semi-products. The same question has to be asked about their composition.

*Composition: iron, low steel, high steel* The question of the production of iron or steel to respond to a demand—as early as the smelting step—can be raised, since some blooms are mainly ferritic or have a low level of steel, while others are mainly steely. Nevertheless, in the proto-historical period, the number of exemplars analysed is currently too low to allow us to propose a serious answer.

Table 1 *A synthesis of the structural characteristics of the iron raw materials, by variants: black, characteristic shared by the majority of objects; grey, characteristic represented by some objects*

| *Macroscopy* | | | | | *Internal texture* | | | | | | | | | | | | | | | *Synthesis* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Inclusional quality* | | | | | *Indicators of reduction process* | | *Shaping techniques* | | | *Composition—treatment* | | | | | |
| *Category* | *Variant* | *Range of weight in grams (min./max.)* | *Number of pieces studied (macroscopy, including published data)* | *Number of pieces analysed (microscopy, including published data)* | *Very bad (>25%)* | *Bad (25–15%)* | *Middle (15–10%)* | *Good (10–5%)* | *Excellent (5–0%)* | *Carbon enrichment around porosities* | *Incomplete agglomeration of metal* | *Deformation of a single mass of metal* | *Assemblage of several masses of metal* | *Shaping by repeated folding* | *Ferrite* | *Low steel (0.05–0.5% C)* | *High steel (0.6–0.9% C)* | *Very high steel (>0.9% C)* | *Peripheral cementation* | |
| Bloom | Compl. | 1 950–12 770 | 7 | 6 | ■ | | | | | ■ | ■ | ■ | | | ■ | ■ | ■ | | | Heavy and short items, close to raw products. |
| Bloom | Frag. | X | 10 | 7 | ■ | | | | | ▒ | | ■ | | | | ▒ | ■ | ▒ | | |
| Bipyramidal | BCS1 | 3 100–10 680 | 68 | 3 | ■ | | | | | | ■ | ■ | | | ■ | ▒ | ▒ | | | |
| Bipyramidal | BCS2 | 2 000–6 400 | 69 | 2 | ■ | | | | | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | |
| Hooked billet | X | 1 000–3 000 | 1 | 2 | ■ | | | | | | ■ | ? | ? | ? | ■ | | | | | |
| Quadrangular | BQL2 | 208–1 245 | 10 | 5 | | ■ | ▒ | ▒ | ■ | ▒ | ▒ | ■ | | | ■ | ▒ | ▒ | | | |
| Bipyramidal | BLS2 | 1 174–1 908 | 4 | 1 | ■ | | | ▒ | | | ■ | ? | | | ■ | ▒ | | | | Heavy and long products, intermediate refining quality. |
| Bipyramidal | BLD1 | 2 985–7 235 | 24 | 3 | ■ | | | ▒ | | ■ | ■ | ■ | | | ■ | ▒ | ▒ | | | |
| Bipyramidal | BCS3 | 1 070–2 465 | 35 | 1 | | ■ | | | | | | | ? | | ■ | ■ | | | | |
| Quadrangular | BQE1 | 1 224–7 000 | 3 | 2 | | ■ | ■ | | | | | ■ | | | ■ | | ▒ | | | |
| Bipyramidal | BLS4 | 2 355–4 300 | 58 | 1 | | | ■ | ■ | | | | ■ | | | ■ | | | | | |
| Currency bar | CBL5 | 451–2 145 | 19 | 3 | | | ■ | ■ | ■ | | | ▒ | ■ | ? | ■ | ▒ | ▒ | | | Long products, weighing several hundreds of grams, very well refined. |
| Currency bar | CBE4 | 628 | 2 | 1 | | | | ■ | ■ | | | ■ | | ■ | ▒ | ■ | | | | |
| Currency bar | CBE3 | 613–737 | 8 | 1 | | | | | ■ | | | ? | | | ■ | ▒ | | | | |
| Currency bar | CBE1 | 391–910 | 121 | 12 | | | ▒ | ▒ | ■ | | | ■ | ■ | ▒ | ■ | ▒ | ▒ | | ▒ | |
| Thin extremity | Draft bar | 18–85 | 3 | 1 | | | | | ■ | | | ■ | | | ▒ | ▒ | ■ | | | Light and small products, perfectly refined. |
| Socket bar | BAD2 | 15–52 | 18 | 4 | | | | ■ | ■ | | | ▒ | ▒ | ■ | ■ | ▒ | ▒ | | | |
| Socket bar | BAD1 | 22–153 | 310 | 28 | | | ▒ | ■ | ■ | | | ▒ | ▒ | ■ | ■ | ■ | ■ | | ■ | |

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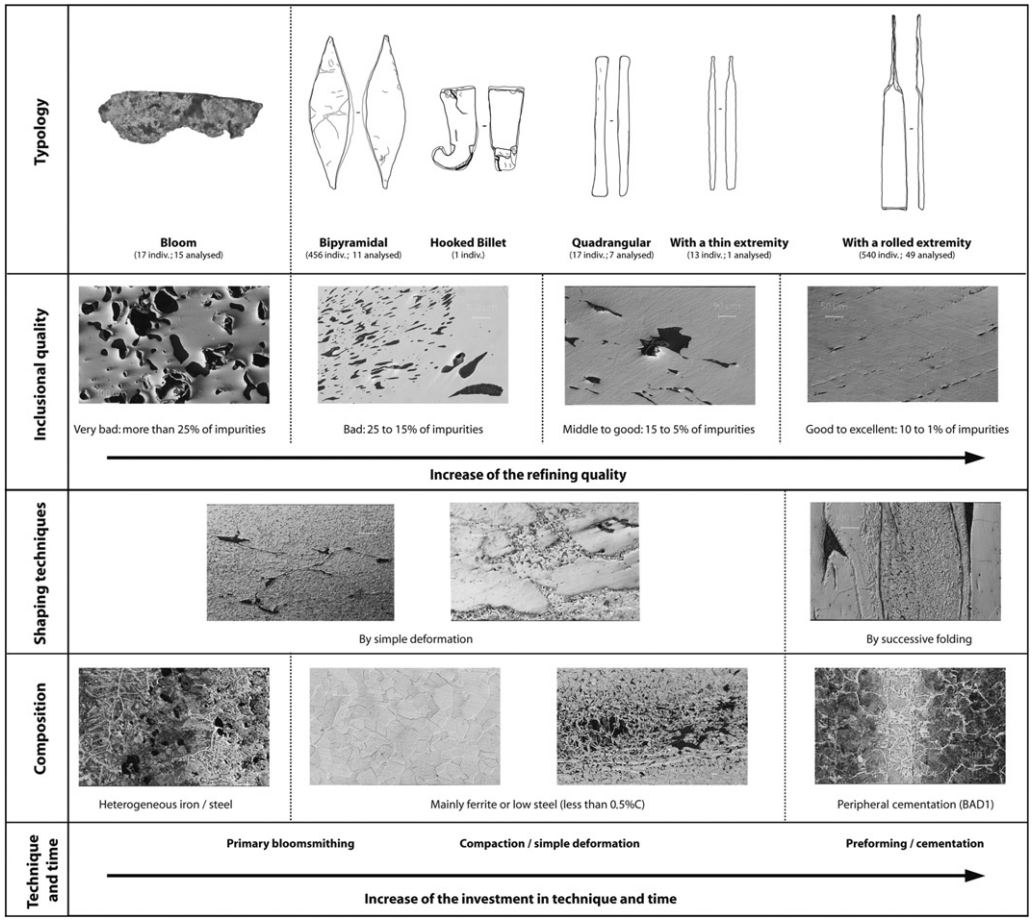


Figure 6 *The morphological and structural characteristics of the raw iron materials by category: the metallographic studies demonstrate a correlation between morphology and structure.*

Within the framework of the production of heterogeneous products, combining iron and steel, is it possible to presume that fragments of crude masses of iron were sorted in order to allow the fabrication of semi-products with a normalized composition? Simple techniques, such as quenching or macroscopical differentiation, taking into account the appearance of the cracks, are ethnographically documented (Coulibaly *et al*. 2000; Fluzin 2002) and allow the separation of iron from steel.

The semi-products studied are mainly ferritic or their carbon content rarely exceeds 0.5 wt% (Table 1). High steel (up to 0.9% C) is only found to be present in a small proportion of the sections studied. Two exceptions are known. The BAD1 'socket bar', for which it seems that the presence of steel has been systematically sought after, and the raw metal fragments which always have a high carbon content of 0.7–1.0% C (Table 1), some of them locally exceeding 2.1% C (cast iron). If the hypothesis that some of these elements were waste cannot be excluded, they could also have been pieces awaiting decarburization, or isolated with the aim of producing specific objects. For some of the crude metal fragments, their high ratio of compaction allows us to

envisage that they were not abandoned because of their high carbon content. In this case, they would probably have been rejected before an advanced work stage that would have been intended to render their surfaces regular, and before having been made denser.

These observations allow us to envisage the circulation of iron/low-steel (less than 0.5–0.6% C) and of a high steel content (0.7–1% C) within differing forms. Steel, as a hard metal, would have circulated in a raw form. Iron semi-products would have then constituted a preferred form for the distribution of materials with a low carbon content. This recalls, in some respects, the medieval Central Pyrenean trade (Verna 2001), where the steely metal, which was heterogeneous in composition, circulated as raw fragments or carelessly shaped bars, which were fragmented in order to extract, macroscopically, the carburized zones.

These observations allow us to reconstruct a normalized production of raw iron materials, making use of a repetitive form and the application of similar fabrication techniques for products of the same category or its variants (Table 1 and Fig. 6).

## UNDERSTANDING THE USE OF RAW METALLIC MATERIALS

The study of each category of semi-products reveals differences in their internal characteristics and in the investment in time of their fabrication, which is probably related to distinct functional destinations. Their discovery context (Table 2) and the fabrication techniques known for the finished objects of the Iron Age seem to confirm this hypothesis. First, these contexts attest to the fact that all categories of semi-products were used for artisanal purposes: all the categories include exemplars with traces of forge transformation (hammering, cutting etc.). The blooms, as the rawest and heaviest products, are those with the largest use possibilities. This is confirmed by the nature of the workshops in which they were found, which indeed vary. They were used for diverse purposes: the production of semi-products, and the fabrication of large or small objects.

Table 2 *A synthesis of the characteristics of the workshops in which the iron raw materials were found (by number of workshops)*

| | | | *Blooms* | *Bipyramidal* | *Quadrangular* | *With a rolled extremity* | *Hooked billet* | *With a thin extremity* |
|---|---|---|---|---|---|---|---|---|
| *Bloom or semi-product with traces of forging* | | | 20 | 2 | 4 | 13 | 1 | 3 |
| Nature of production | Specialized | Small objects | 2 | 1 | | 3 | | |
| | | Sheet metal | 4 | 1 | 2 | 8 | | |
| | | Blades/tools | 2 | | | 7 | | |
| | | Scabbards | | | | 3 | | |
| | | Large objects | 4 | | | | | |
| | Generalist/diverse | | 12 | 1 | 5 | 6 | | 2 |
| Specific techniques | Primary bloomsmithing | | 20 | | 2 | 2 | | |
| | Successive folding | | 4 | | 2 | 9 | | |
| | Welds | | 7 | | 2 | 13 | | |
| | Horn/cementation | | 3 | | | 6 | | |
| | Quenching practices | | 2 | | | 1 | | |
| Total number of workshops | | | *20* | *2* | *6* | *19* | *1* | *3* |

They were also intended for specialized production, such as sheet metal. Their use in this kind of context could reveal a technical choice by artisans wishing to select and prepare their raw materials themselves, in order to obtain objects with an excellent quality.

The function of the bipyramidal forms, and of the hooked-billet and quadrangular forms and the semi-products with a thin extremity, is more difficult to determine, given the small number of workshops in which they were found. Their presence in large artisanal production centres, with a diverse range of object types, suggests a variety of kinds of use. Through a number of their characteristics, the semi-products with a rolled extremity demonstrate a specific production. The fabrication practices reveal a clear investment of time and the use of complex techniques (formation by repeated folding, cementation). It is possible to suggest that they represent a kind of draft form. Their level of preparation suggests a specialized production: the formation by repeated folding allows an orientation of the metal and its homogenization implies very good mechanical properties. The alternation of sheets of metal of differing natures (iron/steel) also provides ductility and resistance. Study of the finished objects demonstrate that these characteristics were researched in the fabrication of weapons (Fluzin *et al*. 1983; Senn Bischofberger 2005), knives, swords (Pleiner 1993; Senn Bischofberger 2005) and tools (Fell 1993, 1995; Fell and Salter 1998; Schwab 2002). Non-heterogeneous zones are also necessary in the production of sheets of metal in order to avoid cracks.

The use of 'currency bars' for the manufacture of swords has previously been envisaged owing to their suggestive morphology, and has resulted in their denomination as '*saumon d'épée*' in France and '*schwertbarren*' in Germany. But until now, there has been little proof available to really confirm this hypothesis. The experiments conducted by Radomir Pleiner (1993) provided the first arguments in support of this proposition: he demonstrated that a 'currency bar' 400 mm long and around 650 g in weight could be transformed as a whole, and by simple deformation, into a 500 g sword, measuring 600–700 mm in length. In the second Iron Age, the length of the swords oscillates between 500 and 900 mm (Rapin 1999), with a weight around 500–600 g (Mathieu 2007). Most of the complete 'currency bars' of the corpus are 540 mm long on average, with an average weight of 775 g, and so could have been used for the manufacturing of swords. Furthermore, this is one of the rare categories of semi-products with a relatively constant mass (mainly between 500 and 700 g), possibly suggesting the hypothesis of a specific use.

The study of workshops brings new data to light that could support this hypothesis. All the workshops where 'currency bars' were found are concerned with the fabrication of blades or tools. In two cases, they were associated with traces of the fabrication of scabbards. An objection to this argument could be their composition: a great proportion of the 'currency bars' consist mainly of ferrite, or their carbon content is low (less than 0.5%C). Nevertheless, this is also the case for a great proportion of the blades (Pleiner 1993). Within this framework, the shaping of the swords could have been made by simple deformation of a single 'currency bar', as a draft object that had already been formed by repeated folds. Alternatively, the successive folds and assemblage of sheet metal by welding could have been done in the workshops where the 'currency bars' were transformed. Mastery of the technique of forming by repeated folding is obvious in all the sites where this type of semi-product has been found.

The hypothesis of a 'draft sword' is not the only one that should be envisaged. These semi-products have also been used after cutting, which reveals a transformation of small pieces of material. It is also obvious that the mass of some bars is too low (between 363 and 450 g) or too high (between 1165 and 2145 g) for the manufacture of swords. Several workshop sectors that produced 'currency bars' demonstrate the fabrication of sheet metal, and two of

them are concerned with the fabrication of scabbards. The quality of refining for this kind of semi-product, and their length, would have been perfectly adapted to the fabrication of this kind of object. Thus, these semi-products could have constituted a first-class material for the fabrication of objects requiring high mechanical properties—weapons and various blades, or tools, the production of which may also have taken place in the same workshops (Table 2).

The fact that the internal characteristics and the morphology of the 'socket bars' are similar to those of the 'currency bars' cannot be accidental. Their conditions of use could have been similar, but for the fabrication of smaller objects (Bauvais 2007; Berranger *et al*. 2007; Berranger 2009a). The BAD1 'socket bar' variant is significant because it contains a non-negligible proportion of steel, coming from a peripheral cementation process, which could have given this variant good mechanical characteristics. The carbon enrichment of a surface increases its hardness. For these semi-products, which were intended to be re-transformed, the operation can also facilitate later steel-to-steel welding by lowering the weldability point (from 1200–1300°C for pure iron to 830–900°C for steel: Fluzin 1983). These draft bars could only enable the fabrication of small objects. This would seem to suggest a specialized production, such as that of small tools such as chisels, hole-punches and so on, or certain objects intended for personal use, such as knife blades or razors.

Several workshops show evidence of the fabrication of sheet metal (Bauvais 2007). The volume of metal corresponding to the 'socket bars' suggests a relatively narrow range of uses, such as bucket hoops, tableware, decorative or reinforcement struts for wooden objects and, of course, scabbards. The discovery of 'socket bars' in workshops concerned with the fabrication of scabbards makes the hypothesis of their use for pieces related to this kind of object a credible one. Indeed, scabbards, as elements lending strength to the overall object, require a very high quality of metal and represent a volume of metal that is quite compatible with that provided by the 'socket bars'.

The analyses of semi-products with a rolled extremity seem to demonstrate the preparation of raw material especially dedicated to the manufacturing of specific products. It is then possible to reconstitute their fabrication for specialized workshops, according to norms, within the framework of a chain of transformation that is highly structured, from the treatment of raw iron to the fabrication of a finished object.

## THE EVOLUTION OF THE ORGANIZATION OF PRODUCTION DURING THE IRON AGE IN FRANCE, FROM THE STUDY OF RAW IRON MATERIALS

Establishing the chronology of semi-products is one of the most difficult aspects of their study, since they have often been discovered outside of datable contexts, or because their discovery is old and poorly documented. In the present study, however, the chronological analysis is based solely upon well-established contexts, and takes into account the totality of the zone where the semi-products are found: from Poland to the British Isles. The majority of the data come, however, from northern and western France, zones that have recently provided well-documented discoveries.

Figure 7 offers a synthesis of the results of this chronological study. It shows an ascendency of bipyramidal semi-products during the sixth to fifth centuries BC. On the other hand, from the third century BC it is the semi-products with a rolled extremity that are the most numerous, and the number of categories of semi-products in circulation increases significantly. This table allows for the isolation of three distinct periods, which we will now discuss.

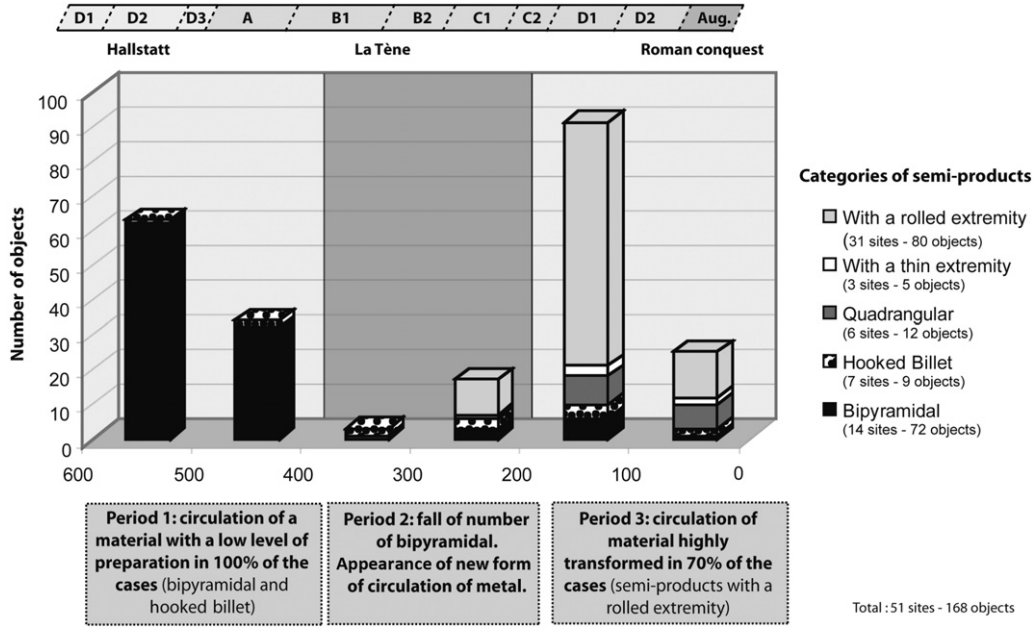


Figure 7 *The number of objects dated, by century and by category of semi-product: only the well-established contexts have been taken in account; and objects belonging to two periods have been counted once for each.*

### *Period 1 (seventh to fifth centuries BC): intense exchanges of iron raw materials in the 'Fürstensitze'/Celtic hill-fort zone*

If this period is characterized by a low diffusion of iron in society, from the fifth century BC the workshops reflect a contrasting situation, in both smelting and post-smelting. Typically, the quantity of wastes suggests a very limited production. But some workshops indicate the possibility of production in large quantitites—in smelting at, for example, La Bazoge (France: Cabboi *et al*. 2007) with 10 tonnes of slag conserved, and in the northern Black Forest (Germany: Gassmann and Wieland 2007); or in post-smelting at Bragny-sur-Saône (France: Flouest 2007) with an estimated 15 tonnes of slag.

The study of the metallic raw materials attributed to this period confirms the perfect mastery of the process of fabrication of iron and the capacity to produce, at least occasionally, significant quantities of metal. The raw blooms coming from Bourges 'St Martin des Champs' (France: Leroy and Merluzzo 2007), the heaviest of which weighs 12 kg, or the semi-products coming from Nottonville 'La pièce de la cave' (France: Lelong *et al*. 1992), the majority of which weigh between 5 and 7 kg, are the clearest evidence of this mastery of smelting techniques. In this period, iron raw materials circulate mainly in the form of voluminous products, such as hooked billets, weighing from 1 to 3 kg, or bipyramidal semi-products, with a mass of between 1 and 8 kg.

The morphological normalization of the bipyramidal semi-products and of the hooked billets allows us to perceive enough flux in the iron trades to generate a circulation of the raw materials according to the reasoned framework. The flattening or torsion of the extremities as a means of

demonstrating the quality of the metal indicates the existence of agreements concerning the information that should be transmitted between the producer and the consumer. For the bipyramidal variants, the analyses of their internal structure do not show significant differences in the quality of the metal or its composition. The most obvious criteria of differentiation are the metrological characteristics. The different forms probably correlate with distinct workshop traditions. Even if the quality of the documentation does not allow a fine typo-chronological study of these semi-products, it is nevertheless possible to demonstrate that several variants were contemporaneous (BLD1, BCS1, BCS2 and BCS3: Berranger 2009a, fig. 54). Known in the same geographical zone, which covers several hundreds of kilometres (Fig. 8), this would testify to their circulation in the entire Hallstattienne zone, within a framework of exchange of not just 'know-how' but also products.

Most of the semi-products (bipyramidals) known from this period have been found outside workshop contexts (Berranger 2009a,b). They have been excluded from the usual economic networks, and have not been transformed in forges. These deposits occur in zones where the most luxurious manifestations of power during the Ha D2/D3-LTA are observed (the 'Fürstensitze'—Celtic hill forts). Developed in societies classed as 'complex chiefdoms' (Brun and Ruby 2008), the manipulation of these valuable reserves was probably carried out in the context of specific ceremonies, intended to reaffirm the power of the elites through the sacrifice of wealth.

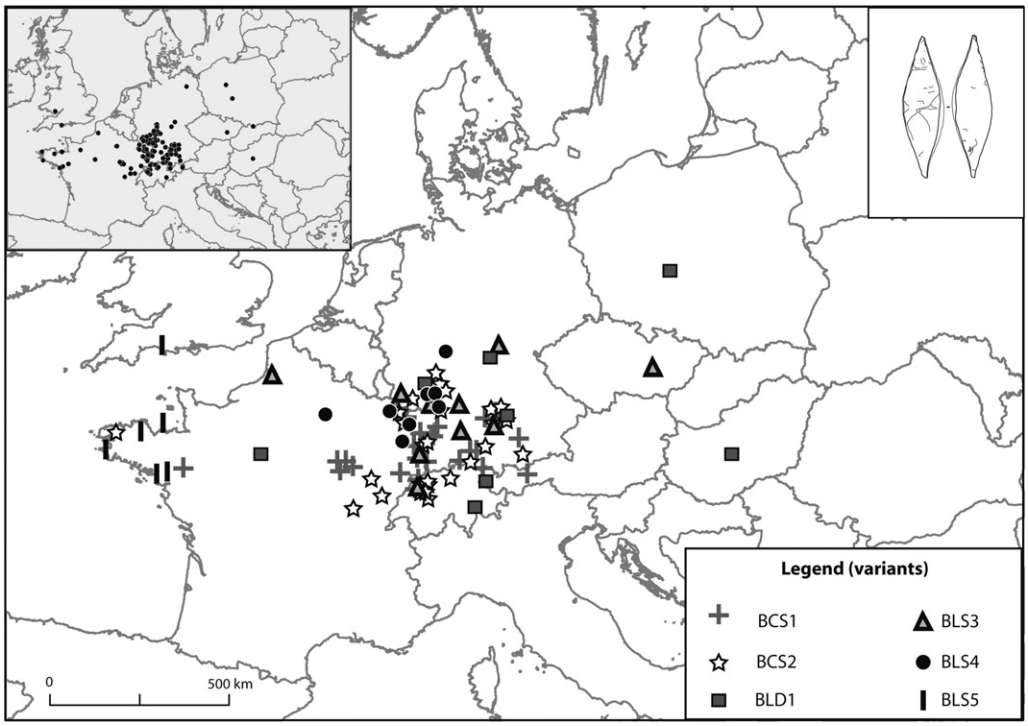


Figure 8 *The distribution of the main variants of bipyramidal semi-products known from the French corpus: grey window, the distribution of the totality of bipyramidals known at the European scale.*

*Period 2 (fourth to third centuries BC): the beginning of a structuralization of the exchanges in response to a diversification of artisanal practices*

The appearance of semi-products with a rolled extremity, during the third century BC, is contemporaneous with the appearance of quadrangular semi-products. In parallel, the circulation of bipyramidals and hooked billets continued. They allowed the exchange of metal of a distinct quality and volume. The quadrangular forms and semi-products with a rolled extremity constituted a form of circulation of a low mass of metal (typically less than 1 kg). Some variants, such as the socket bars, are a clear indication of the production of bars adapted to the fabrication of a single object. The utilization of new categories of semi-products with a better quality of refining is an indication of a less significant investment by the blacksmiths at the primary stage of transformation.

The diversification of volume and quality of metal to be transformed is related to an increasing differentiation of the iron metallurgy practices in forging, and with a greater degree of specialization. Added to the bipyramidals and hooked billets, which were intended for generalist purposes, the semi-products with a rolled extremity are intended for the fabrication of quality products, such as sheet metal or blades. They indicate the evolution of 'specific' markets, developed in the context of a specialized production, carefully planned from the preparation of the raw iron to the fabrication of objects. As previously observed, these norms do not reflect technical traditions of more or less autonomous workshops, but result from a functional normalization that shows interdependence between the different actors in the production chain (smelting–bloomsmithing–forging).

*Period 3 (second to first centuries BC): an increase in the quality of the metal in circulation, diffused at the macro-regional scale*

Continuing from the previous period, the increase in the forms given to the metal in circulation is seen to continue. The semi-products with a thin extremity and the variant BAD1 of the 'socket bars' appeared, and are added to the other categories of semi-products already known (bipyramidals, hooked billets and quadrangular forms with a rolled extremity). As for the first Iron Age, the variants identified seem to testify to the production of semi-products according to a certain functional normalization and the existence of different traditions in workshops. Their circulation does not seem to be organized, as before, according to concurrent exchanges in the same zone, but, on the contrary, it seems to be structured within narrower spaces, at the macro-regional scale (Fig. 9). This could be an indication of the existence of particular controls upon the conditions of their fabrication and circulation, such as specific agreements, the mechanism of which still remains to be characterized. From our study of the workshops, it appears that 'elite' control is exercised through the monopoly of the acquisition of raw metal and through the distribution of the transformed metal (reflecting the centralist role of the agglomeration, and more particularly of the *oppida*: Bauvais 2007; Berranger 2009a).

The increase in the forms given to the metal in circulation also indicates a diversification of the quality of metal and reinforcement of the adequacy of the available raw materials given the kind of object to be produced. The appearance of the BAD1 variants reflects the production of a kind of product that is highly standardized for the fabrication of objects of a certain limited size. Their excellent quality of refining, and their production by repeated folding, after the application of a cementation process, mark them out, in this case, for the fabrication of sheet metal or small objects with excellent mechanical properties. During the same period, hard steel seems to

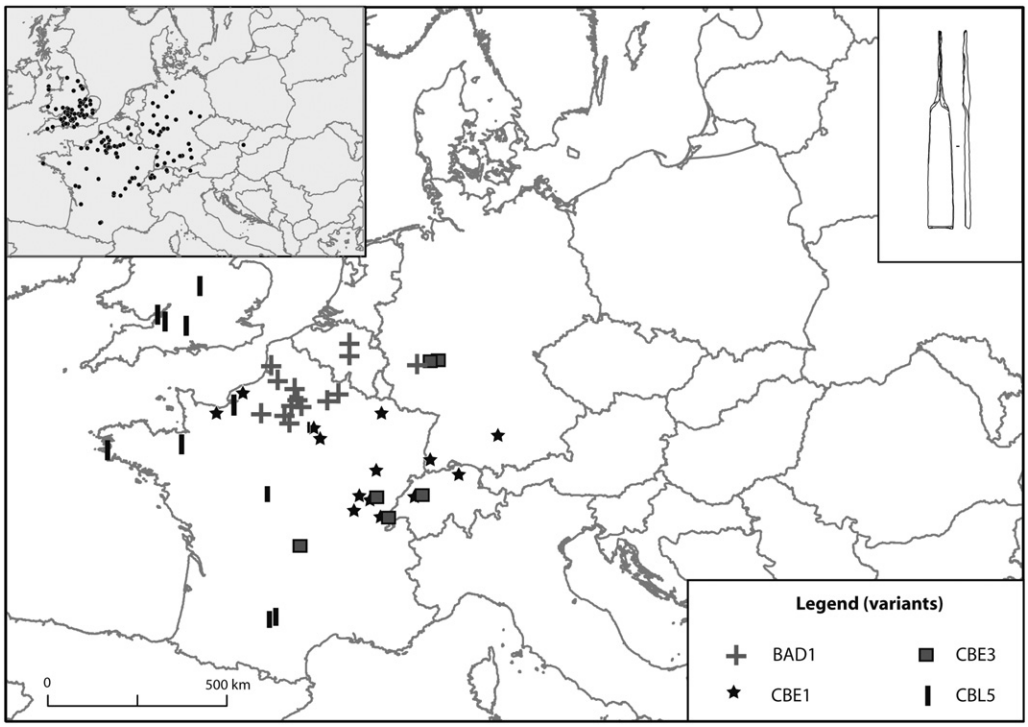


Figure 9 *The distribution of the main variants of semi-products with a rolled extremity known from the French corpus: grey window, distribution of the totality of semi-products with a rolled extremity known at the European scale.*

circulate in a different form, derived from low steel or ferrite. Hard steel would have circulated in the form of crude masses of metal, and low steel was diffused mainly in the form of semi-products.

These characteristics reflect a rationalization and a diversification of the means of acquiring the iron metallic products, which could be correlated with the diversification and greater specialization of the blacksmiths, in the context of an increase in primary production (smelting).

A change in the use of the various forms of semi-products is noticed after the Roman conquest. On the one hand, the exchange of bipyramidals and of hooked billets seems to continue, but in different forms and on a smaller scale. On the other hand, the utilization of semi-products with a rolled extremity is abandoned. There may be many reasons for this: it is possible that the increasing volumes of production could have made it difficult to adapt these objects to the new conditions of production, as 'currency bars' result from long and complex techniques and contain relatively little metal (on average, 775 g). On the contrary, after the Roman conquest, the quadrangular semi-products, which were little known during the Iron Age, seem to become a preferred form for the circulation of iron (Feugère and Serneels 1998; Pagès 2008). Their fabrication is normalized and they can be found in trade relations over a wide area.

The study of the properties of the metallic raw materials suggests that from the end of the Iron Age, the production of semi-products occurred within a highly structured framework. They seem to have circulated according to certain degrees of standardization, in regional network exchanges, and in some cases, to supply specialized markets. It is thus possible to envisage a sophisticated

and complex system of exchange, a characteristic that is, for these periods and for iron metallurgy, difficult to establish owing to the absence of sufficient documentation.

## CONCLUSION

This work, centred upon the characterization of post-smelting activities at the end of the Iron Age, joins a growing body of work investigating these processes in a pioneering perspective, through its focus on a step of the *chaîne opératoire*, which is still insufficiently studied, especially for this period.

This paper has presented evidence of a general evolution according to three main periods. The first period is characterized by the circulation of little prepared iron materials. It is replaced by two other periods marked by an increase in the quality of metal in circulation, and by the diversification and increase of the specialization of metallurgical activities. In light of these observations, a further study is now necessary to refine and qualify the general schema of organization that has been proposed here, which will take into account the more complex realities that can be observed at a smaller regional scale. The new-found interest in these questions by the archaeological community, and especially by proto-historians, and the increasing number of recent discoveries of workshops, are the most concrete bases on which to pursue this future research. The precision of the data made available by macroscopic and microscopic analyses gives greater justification for a more systematic study of metallic wastes, which have been neglected for too long. Our new research programme is now orientated towards systematic analysis of inclusions, in parallel with microscopic observations, in order to study the inclusive or exclusive provenance zones of the metal so that we might consider the dynamics of exchange (Leroy 2010). It also integrates carbon dating of the metal, to obtain better precision concerning the chronology of isolated deposits (bipyramidals: Berranger 2009a). It is now clear that these methods will finally allow us to approach a reconstruction of the framework of production and circulation of a material that has, significantly, given its name to this period of proto-history.

## REFERENCES

Allen, D., 1967, Iron currency bars in Britain, *Proceedings of the Prehistoric Society*, **XXXIII**, 307–35.

Bauvais, S., 2007, *Evolution de l'organisation des activités de forge dans le nord du Bassin parisien au second âge du fer, Etudes pluridisciplinaires de la chaîne opératoire en métallurgie du fer*, Ph.D. thesis, Université de Technologie de Belfort-Montbéliard.

Berranger, M., 2009a, *Le fer, entre matière première et moyen d'échange, en France du VII^e^ au I^er^ s. av. J.-C.: approches interdisciplinaires*, Ph.D. thesis, Université Paris 1, Panthéon–Sorbonne.

Berranger, M., 2009b, Le commerce du fer, artisans et savoir-faire des gaulois, *Les dossiers de l'archéologie*, no. 335, September–October, 64–7.

Berranger, M., Bauvais, S., and Fluzin, P., 2007, 'Socket bars': multi-disciplinary results (archaeology and archaeometry) on a specific iron semi-product in the northern Parisian basin (France), in *Archaeometallurgy in Europe 2007, international conference in Grado-Aquilea (Italy), 2007*, CD-ROM publication.

Brun, P., and Ruby, P., 2008, *L'âge du fer en France, premières villes, premiers états celtiques*, INRAP collection 'Archéologies de la France', Editions La découverte, Paris.

Cabboi, S., Dunikowski, C., Leroy, M., and Merluzzo, P., 2007, Les systèmes de production sidérurgique chez les Celtes du Nord de la France, in *L'économie du fer protohistorique: de la production à la consommation du métal, XXVIII^e^ colloque AFEAF, Toulouse 20–23 mai 2004* (ed. P. Y. Milcent), *Aquitania*, suppl. **14**(2), 35–62, Bordeaux.

Coulibaly, E., Benoit, P., and Fuzin, P., 2000, Approche des techniques de traitements thermomécaniques et thermochimiques dans la mise en forme des objets chez les forgerons du Bwamu (Mali – Burkina Faso), in *Arts du feu et*

*productions artisanales, actes des XX^e rencontres internationales d'Archéologie et d'histoire d'Antibes, tenues les 21–22–23 octobre 1999* (eds. P. Pétrequin, P. Fluzin, J. Thiriot and P. Benoit), 143–58, Editions APDCA, Antibes.

Crew, P., 1991, The experimental production of prehistoric bar iron, *Historical Metallurgy*, **25**(1), 21–36.

Crew, P., 1994, Currency bars in Great Britain, typology and function, in *La sidérurgie ancienne de l'Est de la France dans son contexte européen, archéologie et archéométrie, actes du colloque de Besançon, 10–13 novembre 1993* (ed. M. Mangin), 345–50, Annales littéraires de l'Université de Besançon, Les Belles Lettres, Paris.

Delamare, F., Nicolas, G., and Mencarelli, E., 1982, Etude du forgeage d'un lingot de fer protohistorique, *Mémoires et études scientifiques de la Revue de métallurgie*, **79**(2), 97–104.

Dieudonné-Glad, N., Parisot, N., Parisot, J., Dupon, E., and Ronchail, F., 2001, Metallographic examination of five flat iron bars with socket from the river Saône (France), *Historical Metallurgy*, **35**(2), 67–73.

Dillmann, P., and L'Héritier, M., 2007, Slag inclusion analyses for studying ferrous alloys employed in French medieval buildings: supply of materials and diffusion of smelting processes, *Journal of Archaeological Science*, **36**, 1810–23.

Doswald, C., 1994, Les lingots de fer en Europe occidentale: problématique générale, in *La sidérurgie ancienne de l'Est de la France dans son contexte européen, archéologie et archéométrie, actes du colloque de Besançon, 10–13 novembre 1993* (ed. M. Mangin), 333–43, Annales littéraires de l'Université de Besançon, Les Belles Lettres, Paris.

Fell, V., 1993, Examination of four Iron Age ferrous hammer heads from Bredon Hill (Hereford and Worcester), England, *Journal of Historical Metallurgy*, **27**(2), 60–9.

Fell, V., 1995, Metallographic examination of Iron Age tools from Somerset, *Journal of Historical Metallurgy*, **29**(1), 1–11.

Fell, V., 2003, Metallographic examination of two Iron Age hooked blocks from England, in *Prehistoric and medieval direct iron smelting in Scandinavia and Europe: aspects of technology and society, proceedings of the Sandjberg conference, 16–20 September 1999* (ed. L. C. Norbach), *Acta Jutlandica*, **LXXVI**(2), 129–33, Humanities Series 75, Aarhus University Press, Aarhus, Denmark.

Fell, V., and Salter, C., 1998, Metallographic examination of seven Iron Age ferrous axeheads from England, *Journal of Historical Metallurgy*, **32**(2), 1–6.

Feugère, M., and Serneels, V., 1998, Production, commerce et utilisation du fer entre l'Ebre et le Rhône: premiers éléments de réflexion, in *Recherches sur l'économie du fer en Méditerranée nord-occidentale* (eds. M. Feugère and V. Serneels), 251–62, Editions Monique Mergoil, Montagnac.

Flouest, J. L., 2007, Approches quantitatives de la production de fer sur le site hallstattien de Bragny-sur-Saône (Saône-et-Loire), in *L'économie du fer protohistorique: de la production à la consommation du métal,* XXVIII^e colloque AFAEF*, Toulouse 20–23 mai 2004* (ed. P. Y. Milcent), *Aquitania*, suppl. **14**(2), 265–70, Bordeaux.

Fluzin, P., 1983, Notions élémentaires de sidérurgie, in *Métallurgies africaines: nouvelles contributions* (ed. N. Echard), 14–44, Mémoires de la société des Africanistes 9, Paris.

Fluzin, P., 2002, The process chain in iron and steel making: archaeological materials and procedures. The contribution of metallographical studies, in *The origins of iron metallurgy in Africa: new lights on its antiquity, west central Africa* (ed. H. Bocoum), 65–96, Editions UNESCO, Paris.

Fluzin, P., Uran, L., Coddet, C., and Beranger, G., 1983, Structures et mise en forme d'armes gauloises, *Revue archéologique de Picardie*, **1**, 181–94, Association pour l'Etude de l'Age du Fer, Amiens.

France-Lanord, A., 1963, Les lingots de fer protohistoriques, *Revue d'histoire de la sidérurgie*, **IV**, 167–78.

Gassmann, G., and Wieland, G., 2007, Systematische Untersuchungen an Eisenproduktionsstätten der Späthallstatt- und Frühlatènezeit im Erzrevier von Neuenbürg, Enzkreis, *Archäologische Ausgrabungen in Baden-Württemberg*, 88–93.

Kleeman, O., 1981, Les lingots de fer bipyramidaux courts et épais: les lingots du type Colmar. Etudes offertes à J.-J. Hatt, *Revue archéologique de l'Est*, **32**, 109–19.

Lelong, A., Aufaure, C., and Conin, A., 1992, *Trésor de fer, la découverte de Nottonville*, Catalogue of an exhibition organized by the Musée des Beau Arts et d'Histoire Naturelle de Châteaudun, 10 July – 20 September 1992.

Leroy, M., and Merluzzo, P., 2007, Déchets d'activités sidérurgiques de Saint Martin des Champs, in *Bourges Avaricum un centre proto-urbain celtique du V^e s. av. J.-C.: les fouilles du quartier Saint-Martin-des-Champs et les découvertes des établissements militaires* (ed. P. Y. Milcent), 175–88, *Bituriga*, monographie 2007-1, Ville de Bourges, Bourges.

Leroy, S., 2010, *Circulation au Moyen Âge des matériaux ferreux issus des Pyrénées ariégeoises et de la Lombardie: apport du couplage des analyses en éléments traces et multivariées*, Ph.D. thesis, Université de technologie de Belfort-Montbéliard.

Mangin, M., 2004, *Le fer*, Collection archéologiques, Editions Errance, Paris.

Mathieu, F., 2007, L'apport des tests expérimentaux à l'étude de l'armement gaulois du III^e s. av. J.-C., *Bulletin Instrumentum*, no. 25, June, 10.

Orengo, L., 2003, *Forges et forgerons dans les habitats laténiens de la Grande Limagne d'Auvergne, fabrication et consommation de produits manufacturés en fer en Gaule à l'Âge du fer*, Monographies instrumentum, 26, Editions Monique Mergoil, Montagnac.

Pagès, G., 2008, *La métallurgie du fer en France méditerranéenne de l'Antiquité au début du Moyen Âge: jalons d'une approche interdisciplinaire.* Ph.D. thesis, Université de Montpellier.

Pleiner, R., 1993, *The Celtic sword*, Clarendon Press, Oxford.

Rapin, A., 1999, L'armement celtique en Europe: chronologie de son évolution technologique du V$^{e}$ au I$^{er}$ s. av. J.-C., *Gladius*, **XIX**, 33–67.

Schwab, R., 2002, Evidence of carburized steel and quench-hardening in the 'Celtic' oppidum of Manching, *Journal of Historical Metallurgy*, **36**(1), 6–16.

Senn Bischofberger, M., 2005, *Das Schmiedehandwerk im nordalpinen Raum von der Eisenzeit bs ins frühe Mittelalter*, Verlag Marie Leidorf GmbH, Rahden/Westf.

Smith, R. A., 1905, Ancient British iron currency bars, *Proceedings of the Society of Antiquaries of London*, **XX**, 179–95.

Verna, C., 2001, *Le temps des moulines: fer, technique et société dans les Pyrénées centrales (XIII$^{e}$–XIV$^{e}$ s.)*, Publications de la Sorbonne, Histoire ancienne et médiévale, 67, Université Paris 1, Panthéon–Sorbonne.